INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2011)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.2410

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Variations of frequency of landfalling typhoons in East China, 1450–1949

Johnny C. L. Chan,[a,b]* Kin-Sik Liu,[a] Ming Xu[b] and Qiuzhen Yang[b]
[a] *Guy Carpenter Asia-Pacific Climate Impact Centre, School of Energy and Environment, City University of Hong Kong, Hong Kong, China*
[b] *Shanghai Typhoon Institute, China Meteorological Administration, China*

ABSTRACT: On the basis of Chinese government records, the number of tropical cyclones making landfall along the East China coast during the period 1450–1949 is examined. The annual number of typhoons making landfall in East China during this period is found to possess a positive and statistically significant trend, as well as oscillations on centennial to decadal timescales. By classifying the years using proxy records of the El Niño and Pacific Decadal Oscillation phenomena, the annual number of typhoon landfall is found to vary with the different phases of these two prominent oscillations, and such variations can be explained to a large extent physically based on modern-day atmospheric data. These results, together with those from previous studies, suggest that variations in the number of landfalling tropical cyclones are largely governed by those in the planetary-scale atmospheric circulations that go through oscillations on various timescales. Copyright © 2011 Royal Meteorological Society

KEY WORDS tropical cyclone landfall; tropical cyclone climate; global warming

Received 10 February 2010; Revised 25 August 2010; Accepted 29 June 2011

1. Introduction

The relationship between global warming and trends in tropical cyclone activity has been hotly debated in the last few years, with different researchers presenting different points of view (see review in Shepherd and Knutson, 2007). A crucial point of contention is the veracity of the data especially prior to, or even during the early years of, the era of meteorological satellites as most tropical cyclones occur over the open ocean, where observations have always been scarce. On the other hand, the number of tropical cyclones making landfall should be much more reliable, as either meteorological or other government records should have documented most of these events. Therefore, an examination of the landfall frequency of tropical cyclones at various locations could provide some clue as to whether any such trends existed in the past. After all, the trend in tropical cyclone landfall frequency should be of important concern to the society.

Landsea (2007) examined records of hurricane landfall in the United States from 1900 to the present. Chan and Xu (2009) also analysed best-track data from various countries and agencies to study variations of frequency of tropical cyclone landfall in East Asia during the past 60 years. Kubota and Chan (2009) studied landfall in the Philippines during the past 100 years and found decadal variations that are related to the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). In all these studies, no linear trend was found. However, with only about 60–100 years of data, variations on much longer timescale cannot be ascertained. Some proxy studies have been carried out to address this issue (Donnelly and Woodruff, 2007; Nyberg *et al*., 2007), but because the results are based on proxy data, uncertainties are always another point of contention.

In China, government records at central, provincial and local levels of all types of natural hazards for at least the past 500 years are available. It is therefore possible to examine these records to identify possible trends or cycles of tropical cyclones making landfall in various parts of China. Chan and Shi (2000) examined such records for typhoons making landfall in the Guangdong Province of China for the period 1470–1931 and found a positive trend in addition to centennial and decadal cycles. In this paper, we present a similar study for the other coastal provinces of East China (Figure 1) for the period 1450–1949.

The description of the data and methodology are given in Section 2. Results of trends and periodicities are presented in Section 3, followed by possible correlations with ENSO and PDO. A summary is given in Section 4.

2. Data and methodology

Tropical cyclone data for the present study are obtained from reconstructed typhoon data in East China. The government historical reports and other special historical reports for the period 1450–1949 are examined and records of all events of typhoons affecting one or more of

* Correspondence to: Johnny C. L. Chan, School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China. E-mail: johnny.chan@cityu.edu.hk

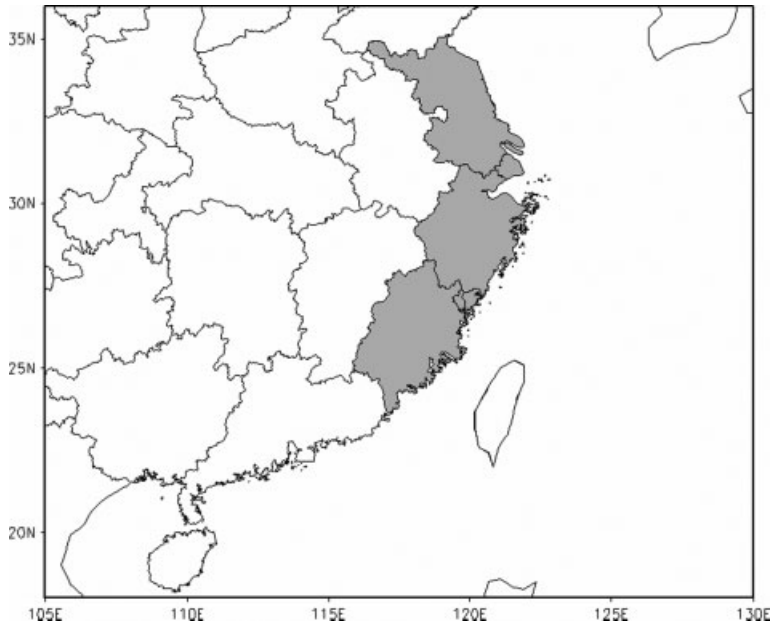

Figure 1. Map of eastern China. The shaded area indicates the three provinces (Fujian, Zhejiang and Jiangsu) of East China in which the frequency of typhoon landfall is studied in this article.

the cities or counties are compiled. Each record describes the event in terms of flood, storm surge, and wind damage. Because a typhoon is likely to have affected more than one city or county, records from different cities and counties that described an event occurring on the same or on the following day are considered to be of the same event. The number of landfalling typhoons each year is then the total number of tropical cyclone occurrences that were separated by more than a few days. Here, East China refers to three provinces: Fujian, Zhejiang and Jiangsu, as shown in Figure 1.

Because the damage from weak tropical cyclones tends to be less, such damage might not have been recorded or reported. What was written in the historical records is likely to be the damage caused by stronger tropical cyclones. It is therefore assumed that the tropical cyclones in this study would be those with intensity close to a typhoon (maximum sustained winds >33 m $\cdot$ s^{-1}), and the term typhoon is used hereafter.

It should be pointed out that the data are from a variety of sources (too many to reference and all in Chinese) and are almost continuous in time with the exception of a few years here and there, either due to unsuccessful retrieval of the documents or due to war. Nevertheless, we consider that we have performed the most comprehensive search of available documents and the data so retrieved represent to a large extent the actual number of typhoons. The validity of the data can also be inferred from the analyses in Section 3 that the periodicities and the correlations with ENSO and PDO so identified are consistent with those obtained from present-day data.

The historical El Niño (EN) dataset is based on tree-ring reconstruction by Cook *et al*. (2000). The period of record is 1408–1978. To study the flow anomalies in EN and La Niña (LN) years for the period 1958–1997, the definitions are based on the information from the US Climate Prediction Center (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.)

The PDO data are based on the reconstruction from Shen *et al*. (2006) who reconstructed the annual values of PDO based on the summer rainfall over eastern China. The data period is between 1470 and 1998. To study the flow anomalies associated with positive and negative phases of the PDO, the standardized PDO index given in the website http://jisao.washington.edu/pdo/for the period 1958 to 1997 is used. A PDO+ year is one in which the average PDO index from the previous December to the current February is >0.4 and a PDO− year is one in which the average standardized PDO index from the previous December to the current February is <-0.4.

The flow patterns associated with different phases of ENSO and PDO are examined using the US National Center for Atmospheric Research (NCAR) / National Centers for Environmental Prediction (NCEP) reanalysis dataset for the period 1958–1997.

3. Results

The annual number of landfalling typhoons (N_T) in East China is found to have large variations on many timescales (Figure 2(a)). In addition, even with the possibility that some of the weaker tropical cyclones might not have been documented, some of the peak values in the time series shown in Figure 2(a) are comparable or even larger than those of the present-day era (Chan and Xu, 2009), with many years having six or seven landfall cases. Such a result is similar to that found by Nyberg *et al*. (2007), who examined the number of landfalling tropical cyclones in the Atlantic during the past 270 years.

A long-term linear positive trend is also evident, with a rate of $\sim$0.3 per century. Although only 7%

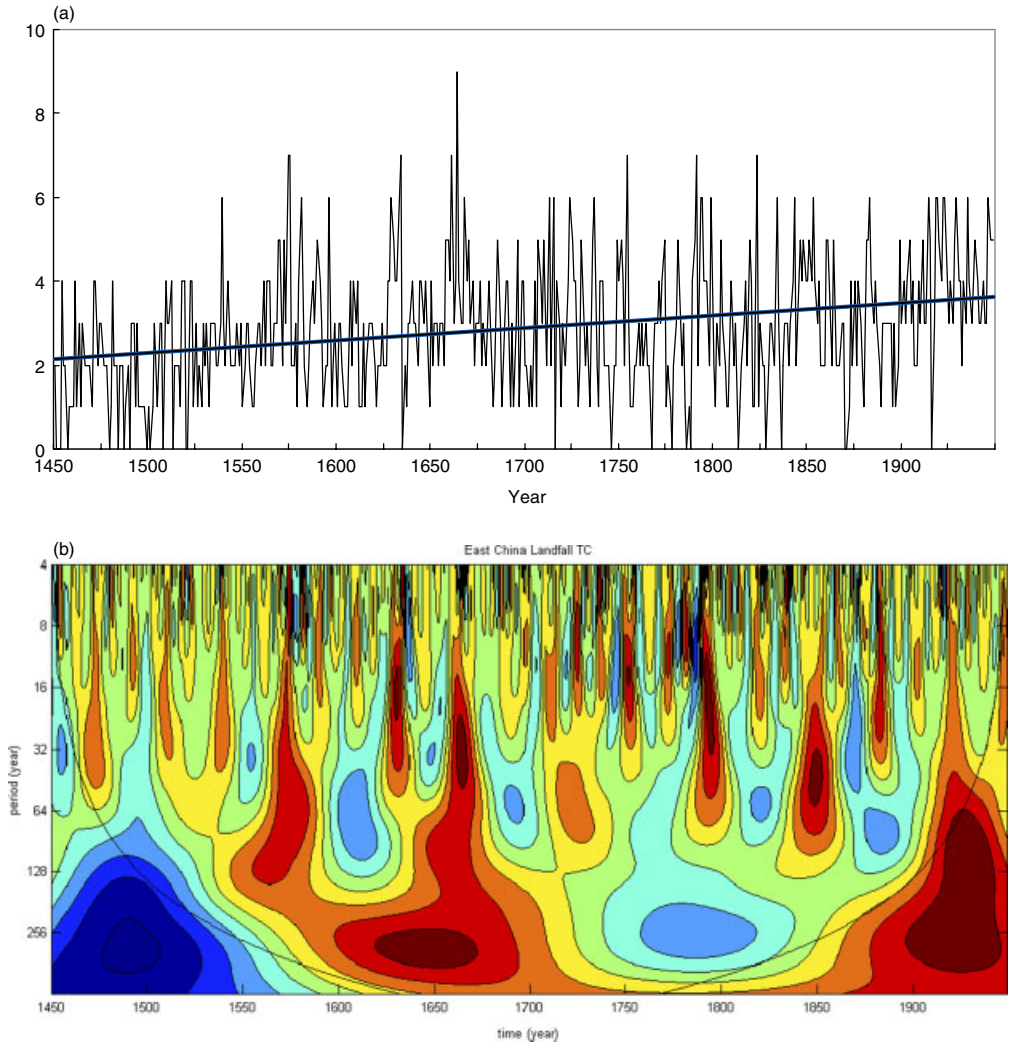

Figure 2. (a) Annual number of typhoons making landfall in East China during 1450–1949. The thick straight line represents the linear trend. (b) Wavelet analysis of the time series in (a). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

of the variance is explained, the trend is significant at the 99% level due to the large number of data points. As this ascending trend may be due to an increasing number of available historical records with time, the trends in the time series for the periods 1500–1949 and 1550–1900 are also examined. The results are very similar (not shown), with the trends again passing the 99% significance test. In other words, a long-term rising trend appears to be present in the frequency of landfalling typhoons in East China. Whether or not such a trend is related to the availability of records cannot be ascertained, but it obviously cannot be attributed to the effect of global warming.

Variations in the landfall frequency on various time-scales are investigated by applying a wavelet analysis with a Mexican hat wavelet (Figure 2(b)). The results suggest that N_T has some prominent periodicities: ~250, 32–64 and 4–8 years. The more than 200-year cycle was also found by Chan and Shi (2000), who studied typhoon landfall in southern China. Some of the possible controls on these periodicities are discussed in the following paragraphs.

The 32–64 period suggests that the variation in N_T may be related to the PDO. However, a correlation between the PDO index and N_T for the period 1470–1949 is −0.08, which might be expected because when the PDO is in its neutral state, it is not likely to have a significant forcing on N_T. A better way to identify a possible relationship lies in examining years in which the PDO is in its positive or negative state. The average value of N_T in positive PDO (PDO+, i.e. PDO index is >0.5) years is found to be smaller than that in negative PDO (PDO−, i.e. PDO index is <−0.5) years (Table I), and the difference is significant at the 95% level.

The 4–8-year period is likely to be related to ENSO as many studies have also found a similar relationship between ENSO and variations in Tropical Cyclone (TC) activity in the western North Pacific (see reviews in Chan, 2004, 2005). However, similar to the situation for the PDO, the correlation between annual landfall numbers and the annual average value of the ENSO index is again statistically insignificant. Chan and Zhou (2005) have shown that the superposition of the PDO and ENSO effects can cause the subtropical high pressure system to

be of different strengths. It is therefore useful to study years in which the PDO and ENSO have either the same or opposite sign.

Using ENSO as the primary classification, it is found that in LN years, N_T is higher if that year is in a PDO− than in a PDO+ state, with the difference being significant at 99% level (Table II). On the other hand, in EN years, the difference in N_T between PDO− and PDO+ years is not significant.

The understanding of these results requires an analysis of the strength of the subtropical high under different situations. However, no atmospheric data are available thus far. The alternative is to use modern data and classify the years in the same way as in the past. During the last 60 years in which reanalysis data are available, it is generally recognized that PDO is in its negative phase during 1947–1976 and positive during 1977–1997 (see the discussion in http://jisao.washington.edu/pdo/). Composites of the 500-hPa anomalies for the months of July to September (during which the largest number of landfall TCs occur in East China) show that during the PDO− era (1958–1976), easterly anomalies exist over the East China Sea, while westerly anomalies are found during the PDO+ era (1977–1997) (Figure 3). Thus, TCs are more easily steered towards East China during the PDO− era and hence N_T is higher, as shown in Table I.

In a LN year, if the PDO index is negative, easterly anomalies again prevail in the East China Sea and East China, while the flow is weak if the PDO index is positive (Figure 4(a) and (b)). This difference again explains why N_T is higher in PDO− and LN years (Table II). In EN years, the flow patterns in the East China Sea and East China are similar in both PDO+ and PDO− years (Figure 4(c) and (d)), and thus, the difference in N_T is not significant.

Table I. Mean number of typhoons making landfall in East China in PDO+ and PDO− years during the period 1470–1949.

PDO status	Number of years	Mean number of typhoons	Standard deviation
PDO+	89	2.74	1.66
PDO−	167	3.28	1.55

The t value for testing the difference between the two is 2.50 and significant at the 95% level.

Table II. Mean number of typhoons making landfall in East China in EN and LN years with the year being in either the PDO+ or PDO− state during the period 1512–1949.

PDO status	Number of years	Mean number of typhoons	Standard deviation
EN			
PDO+	34	3.41	1.62
PDO−	55	3.18	1.47
$t = 0.68$ (not significant)			
LN			
PDO+	16	2.38	1.46
PDO−	31	3.36	1.02
$t = 2.41$ (significant at 99%)			

The t value is for testing the difference between the two states.

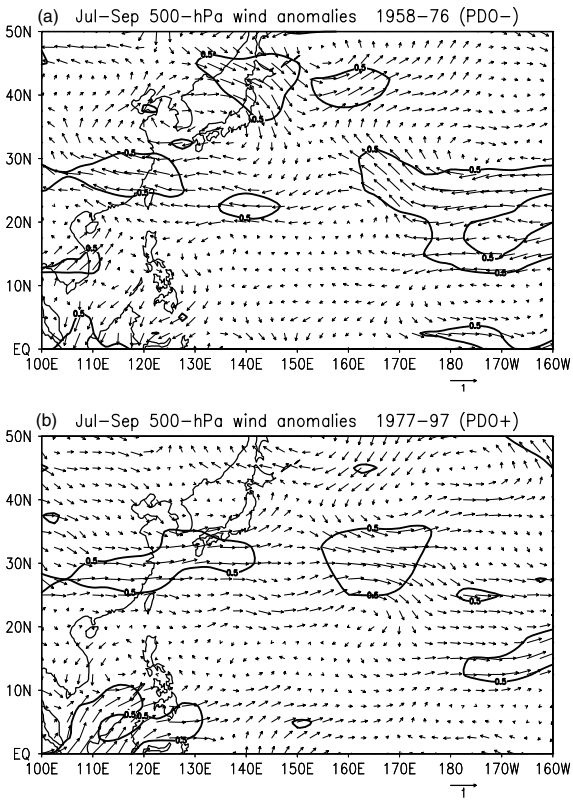

Figure 3. July to September flow anomalies at 500 hPa during (a) PDO− (1958–1976) and (b) PDO+ (1977–1997) periods. Length of the arrow indicates the magnitude of the anomalies, with the scale indicated on the lower right hand corner (unit: $m \cdot s^{-1}$). Contours are isotachs in intervals of 0.5 $m \cdot s^{-1}$.

The results based on the historical data can therefore be explained physically using modern data and hence should be robust. In other words, variations in N_T can be explained to a large extent by variations in ENSO and PDO.

4. Summary

On the basis of past government records, it has been found that the frequency of annual tropical cyclone landfall in East China has undergone significant variations with periods ranging from centennial to decadal. The peak amplitudes have similar values to those from present-day records. A significant trend can also be identified although such a trend can hardly be attributed to the effect of global warming. Whether it is due to an increase in the availability of data records or is physical is unknown.

The decadal to multi-decadal variations are apparently related to those of ENSO and PDO. During cold (negative) PDO phases, easterlies tend to prevail between 20 and 30°N in the western North Pacific, so that TCs tend to move westward and make landfall in East China, and

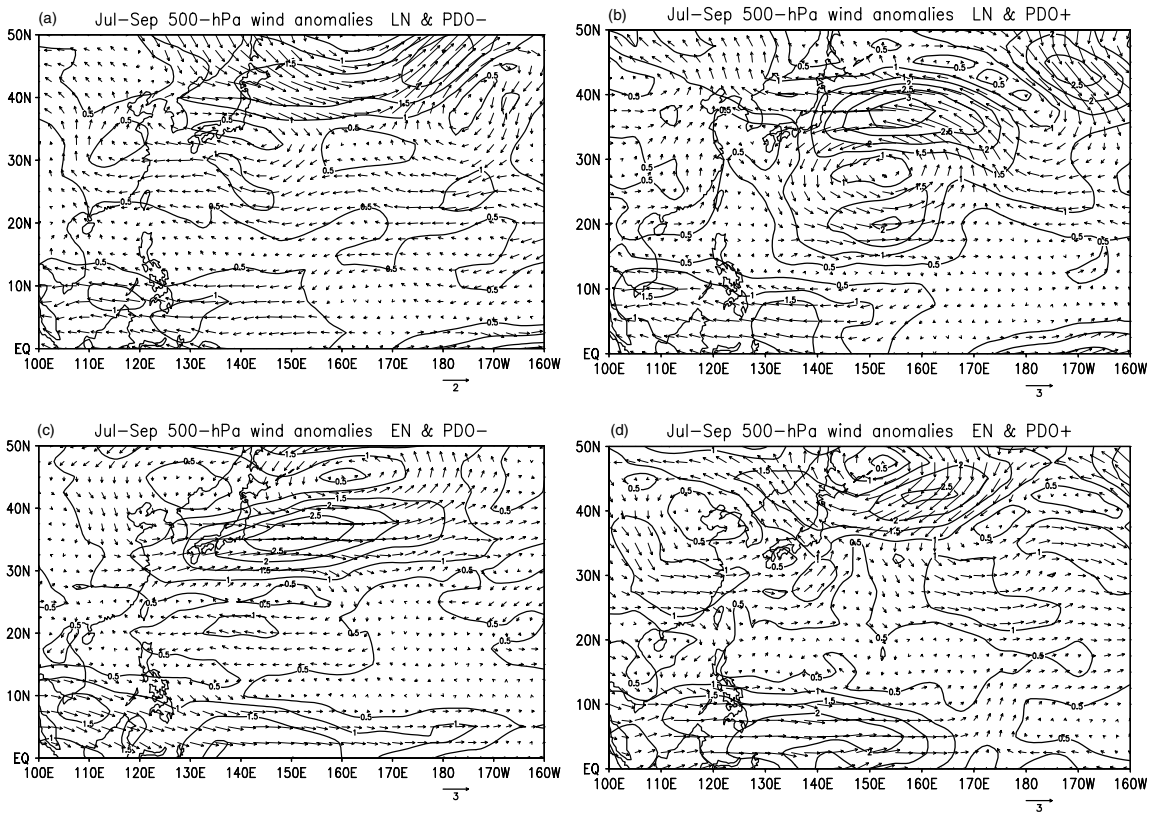

Figure 4. July to September flow anomalies at 500 hPa during LN and PDO− (a), LN and PDO+ (b), EN and PDO− (c), and EN and PDO+ (d) years during the period 1958–1997. Length of the arrow indicates the magnitude of the anomalies, with the scale indicated on the lower right hand corner (unit: $m \cdot s^{-1}$) in each panel. Contours are isotachs in intervals of 0.5 $m \cdot s^{-1}$.

hence, the number of TCs making landfall there is larger than that during a warm (positive) PDO phase when the reverse is true. In the presence of a LN, the easterlies associated with a cold PDO phase are enhanced, and thus, more TCs make landfall in East China compared with a warm PDO phase. However, when an EN is present, the two effects apparently cancel each other so that no significant difference can be identified between a cold and a warm PDO phase.

Together with the result of previous studies (Chan and Shi, 2000; Chan and Xu, 2009; Kubota and Chan, 2009), it may be concluded that the frequency of annual number of landfalling TCs in East Asia goes through large decadal to multi-decadal variations so that any trend that may be present due to global warming is not likely identifiable. From a mitigation and adaptation point of view, attempts should therefore be made to identify such periodicities rather than a linear trend.

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